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# A Single-Feed, High-Gain, Circularly Polarized S-Band Antenna and Its Test Coupler

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**Lincoln Laboratory**
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LEXINGTON, MASSACHUSETTS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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# A SINGLE-FEED, HIGH-GAIN, CIRCULARLY POLARIZED S-BAND ANTENNA AND ITS TEST COUPLER

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*Group 61*

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## ABSTRACT

The development of a single-feed, high-gain, circularly polarized "cup-dipole" antenna, operated over the frequency band of 2.24-2.25 GHz, and its test coupler is described. The antenna consists of a turnstile feed of crossed dipoles of unequal lengths, backed by a cup cavity. With a cup size of 1.33$\lambda$ in diameter, it produces a gain of 12.7 dB when matched to a VSWR of 1.1. This corresponds to an effective receiving area 6% larger than the physical area. An even higher gain of 13.4 dB, or an aperture efficiency of 122.5%, is observed when the antenna is flush-mounted on a large plate. The radiation pattern shows that the antenna has a half-power beamwidth of $\sim 40^{\circ}$ and an axial ratio of $\leq 0.5$ dB over the angular region of $\pm 10^{\circ}$ off boresight.

The test coupler, which is used to test the performance of the antenna without the necessity for radiating into free space, can attenuate the transmitted signal by 30.5 dB. For a good detection of axial ratio, the coupler needs to be separated at least 0.8$\lambda$ from the antenna.

Accepted for the Air Force
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## I. Introduction

Modern communication satellites are often required to carry a number of antennas for the purpose of multiple communication links. Since the spacecraft also carries a large number and variety of electronic and optical apparatuses mounted external to its main body, the space available for the installation of antennas is extremely limited. In addition, the arrangement of the antennas is further restricted by the requirement that the physical appearance of one antenna must not interfere with the communication links served by the other antennas. Therefore, it becomes obvious that there is a need for small, compact, high-gain antennas, capable of being flush-mounted.

It is upon this need that an antenna, designated as a "cup-dipole," was developed, which is the main subject of this presentation. The antenna consists of a right circular cylindrical cavity of which one end is open, and a turnstile feed that has crossed dipoles of unequal lengths. The crossed dipoles are fed from and supported by a single split-tube balun (See Figs. 1 and 2). This

feeding method eliminates the use of a phasing network which is necessary when the two dipoles are fed separately, and thus simplifies the fabrication of the antenna. It was possible to use this approach because of the narrow frequency bandwidth (<0.5%). However, it also generates difficulties in the matching of the device.

To ensure that the TLM transmitter and antenna when mounted on the satellite are in normal operating condition without the necessity for radiating into free space, an apparatus known as a test coupler was also developed. This device is designed to detect directly the radiated power level, as well as the axial ratio, of the radiation from the antenna. A full-length discussion of this device will be made in the second part of this presentation.

## II. Cup-Dipole

In this section, a step-by-step development of the "cup-dipole" antenna will be described. Briefly speaking, it was degenerated from a prototype telemetry antenna that was designed based upon the short-backfire (SBF) concept [1]. It was found that the antenna showed a significant improvement in its gain and axial ratio with the backfiring reflector disk removed, provided the height of the rim for the cavity as well as the height of the feed above the bottom of the cavity were properly adjusted.

### A. Turnstile or Crossed-Dipole Feed

In order for the antenna to be circularly polarized, a turnstile

feed consisting of crossed dipoles which are connected together and fed from a single split-tube balun was designed (Fig. 1). The balun can be filled with dielectric to prevent the occurrence of multipactor breakdown (Fig. 2). In each dipole pair, one dipole is chosen to be slightly longer and the other dipole slightly shorter than their resonant lengths. If the dipole lengths are correctly selected such that the longer dipole, which is inductive, has an impedance, say, $Z_L = a + jb$, whereas a capacitive impedance of $Z_S = b - ja$ is exhibited by the shorter dipole; phase quadrature between the currents in the two dipoles is obtained. Using available tables [2], these optimum lengths are found to be $0.5\lambda$ and $0.35\lambda$ ($\lambda$ = wavelength) if the dipoles are made of rods of 0.05 inch ($0.009525\lambda$) in diameter at the design frequency of 2.245 GHz. These results are valid provided the center gap at the feed point of each dipole is infinitesimally small. This assumption certainly does not hold for the turnstile feed, for which the dipole rods are separated by the diameter of the balun. Moreover, the dipole rods need to be thicker near the feed so that the mechanical strength of the structure can be enhanced. Therefore, the dipole lengths must be modified slightly from the theoretical in order that circular polarization can be obtained. For our experimental models, four short cylindrical posts with threaded holes were attached to the outer wall of the coaxial tube; the dipole lengths were varied by screwing the rods which are threaded at one end.

This has the advantage that the lengths are readjustable which is a requirement at the development stage. As it will be shown later, the dipole lengths after adjustment minus the diameter of the balun feed are indeed very close to the calculated values.

The balun that is used to feed the crossed dipoles has a split-tube configuration and two shorting posts are used, one for each dipole. For the experimental model of Fig. 1 which was first made, the length of the slots was chosen to be $\lambda/4$. For the model of Fig. 2, the slot length has been adjusted for the matching of the device. This will be discussed later in detail.

B. Cup-Dipole vs SBF Antenna

Since the SBF antenna configuration has been proven to be a highly directive radiator and is capable of being flush-mounted, it was first selected for the design of the telemetry antenna for our purpose. Figure 3 illustrates the geometry of the experimental model designed at 2.245 GHz, which could be adjusted to have the following physical dimensions:

| | | | | |
|---|---|---|---|---|
| D | = | diameter of open-ended cavity | = | $1.33\lambda$ or $1.87\lambda$ |
| d | = | diameter of reflector disk | = | $0.3\lambda$, $0.4\lambda$, or $0.5\lambda$ |
| H | = | height of crossed-dipole feed above bottom of cavity | = | $0.25\lambda$ |
| $H_1$ | = | height of reflector disk above bottom of cavity | = | $0.5\lambda$ |

$h \quad = \quad$ rim height or depth of cavity $\quad = \quad 0.25\lambda$

Photographs of this model without the reflector disk and the supporting rod are shown in Fig. 1. Note that in order to vary D, the large reflector plate has two circular slots on which the rim is mounted.

Attempts were first made to obtain an axial ratio of $\leq 1$ dB over the angular region of $\pm 10°$ about boresight, by adjusting the lengths of the dipole rods. It was found that among the three reflector disks tested, only the smallest yields an acceptable axial ratio of $\leq 0.5$ dB for either value of D. For the two larger ones, the best that could be obtained is $\sim 6$ dB for $d = 0.4\lambda$ and $\sim 10$ dB for $d = 0.5\lambda$. With the smallest reflector disk used, the gain of the antenna is found to be 8.6 dB for $D = 1.33\lambda$, but only 6.9 dB for $D = 1.87\lambda$. This is a rather surprising discovery since one normally would expect that a larger aperture would yield a higher gain. Further efforts were made to increase the gain by adjusting H but only a slight increase of 0.1 dB was observed and the axial ratios at the same time went up to $\sim 1.2$ dB for $D = 1.87\lambda$ and $\sim 1.5$ dB for $D = 1.33\lambda$.

Since the antenna showed improved performance with the smaller reflector disk, it was thought perhaps it would be better off without the reflector disk. Without changing the other physical dimensions of the device, this assumption was experimentally proved to be right. The new configuration was then called a "cup-dipole," mainly because of its physical appear-

ance. Since its operation is characterized by the radiation from the aperture of the back-up cavity excited by the crossed-dipole feed as well as the radiation from the feed itself, it is felt that the antenna performance could be improved by varying the rim height or the depth of cavity, h, and the spacing between the feed and the reflecting surface, H. Based upon this postulation, extensive experiments were conducted to observe the variation in antenna performance upon the changes in these parameters. It was found that for every change in h, both H and the dipole lengths had to be readjusted, although the changes in the latter were very small. Selected data from measurements for the cup-dipole with $D = 1.87\lambda$ are illustrated in Fig. 4 in which the axial ratio and gain of the antenna are plotted versus the rim height, with the appropriate value of $H/\lambda$ indicated at each data point. The VSWR of the device was found to be 2.7 and it showed only slight variation when h or H was varied. This indicates that the VSWR of the device is primarily determined by the matching of its feed and is insensitive to the dimensions of the cup-cavity. Similar plots for $D = 1.33\lambda$ are illustrated in Fig. 5. The VSWR was found to vary from 2.8 to 2.9; again, it is insensitive to the changes in h and H.

Comparing the results in Fig. 4 and Fig. 5, one may find the highest measured gain of the antenna is nearly the same when either rim is used, but the axial ratio is better when the smaller one is used. To determine the

best available gain of the antenna, a double-stub tuner was attached to the input to match the device to a nearly perfect VSWR of 1.02. The gain then becomes 12.7 dB for D = 1.33λ, 12.4 dB for D = 1.87λ. Obviously, the smaller cup diameter of D = 1.33λ is the better choice and discussions hereinafter will be referred to this configuration.

The performance of the cup-dipole in the case of being flush-mounted in a ground plate was also tested. The antenna was placed to the edge of one side of a large metal plate of 6λ x 6λ in size to simulate its mounting on a satellite. It was found the optimum values for h and H remain unchanged and, with the double-stub tuner which tuned the VSWR down to 1.07, the gain was found to increase to 13.4 dB. This is to be expected since more energy is radiated to the front of the antenna due to the large ground plane presented by the metal plate.

C. Matching

For the purpose of matching the device, a second model was fabricated, which is shown in Fig. 2. To achieve a good match, the slot length of the balun section was adjusted to match out the reactive part of the antenna impedance, the real part was matched by the use of a quarter-wave transformer. Based on the impedance measurement performed on the prototype and the equivalent circuit for the balun [3], the slot length was estimated to be in the range of 7'' to 9''. In making these estimates, the charac-

teristic impedance of the slotted section was derived from the approximate solution [4] for the air-filled case, assuming the change in this characteristic impedance due to dielectric is the same as that for coaxial cable. Since no certainty of the right slot length could be made theoretically, three coaxial tubes with different slot lengths of 7'', 8'' and 9'' were made for experimental testing.

The measured performance of the cup-dipole for the three feeds are tabulated in Table I. The normalized input impedances of the device were measured, from which the termination impedances referred to the input end of the slotted balun were calculated, based on an estimation of the electrical lengths between the input of the device and the balun. The results are illustrated on the Smith Chart in Fig. 6. It is quite clear that the optimum slot length seems to be ~0. 9 inch, which almost completely matches out the reactance of the crossed-dipole. Based on the impedance with the 0. 9 inch, a quarter-wave transformer was designed; however, its optimum location referred to the input end of the balun still needed to be determined experimentally because of possible errors in estimating the electrical length between the input and the balun section of the device. Subsequent testing of the device showed that if the quarter-wave transformer is placed 0. 05'' below the end of the slotted balun, a good match was achieved, with a VSWR of $\leq$ 1. 1 over the frequency band of 2. 24 to 2. 25 GHz.

TABLE I

Performance of Cup-Dipole for Different Lengths of Slotted Balun

| Slot length (inches) | VSWR | Gain (dB) (unmatched) | Axial Ratio Within $\pm 10°$ off Boresight (dB) |
|---|---|---|---|
| 0.7" | 2.6 | 11.4 | $\leq 0.4$ |
| 0.8" | 2.0 | 12 | $\leq 0.6$ |
| 0.9" | 1.8 | 12.3 | $\leq 0.5$ |

The final measured gain of the cup-dipole matched with the transformer was found to be 12.7 dB, which is the same as that obtained from the prototype model matched with the aid of a double-stub tuner. In fact, for the second model, the rim height of the cup cavity was made continuously adjustable so that the optimum rim height determined from the previous model could be checked. It turned out the same value was observed, namely, $h/\lambda = 0.383$; in addition, the optimum value for $H/\lambda$ was found to remain at $0.376\lambda$.

For the matched cup-dipole, the lengths of the longer dipole and the shorter dipole, neglecting the diameter of the coaxial feed, are found to be $0.48\lambda$ and $0.38\lambda$, respectively.

D. Radiation Characteristics and Antenna Efficiency

The measured radiation patterns for the cup-dipole antenna are shown in Fig. 7 in which the span of cross-hatched area indicates the axial ratio. Note that also shown are the patterns for linear polarization that is parallel to ( horizontal polarization) or perpendicular ( vertical polarization) to the ground. From Fig. 7 it is seen that the half-power beamwidth of the antenna is about 40°.

It is known that [3] the highest gain that can be obtained with uniform illumination and constant-phase distribution over the aperture is given by

$$G_o = 4\pi \frac{A}{\lambda^2} \tag{1}$$

where A is the area of the aperture. Considering the aperture of the cup-dipole, the value of $G_o$ turns out to be 12.46 dB. This is lower than the measured gain of the antenna which is G = 12.7 dB. Therefore, the efficiency of the cup-dipole is

$$\eta = G - G_o = 0.24 \text{ dB or } 106\% . \tag{2}$$

With the antenna flush-mounted, the efficient is raised to 122.5%. This high aperture efficiency certainly makes the cup-dipole very desirable for telemetry applications.

## III. Test Coupler

When an antenna is mounted on a spacecraft, it is necessary to make certain before launching that the antenna is in normal operating condition. Since it is often impossible to perform any standard free-space measurements just before launch, an apparatus known as a test coupler is needed. Figure 8 shows a photograph of the test coupler that can be adapted to the cup-dipole in Fig. 2. The construction of the device is illustrated in Fig. 9. It consists of a metal tube whose diameter is slightly larger than that of the rim of the antenna so that the entire antenna aperture is covered. It was hoped that the radiation from the antenna could be successfully converted into $TE_{11}$ mode propagation in the test coupler. To damp out possible higher modes and thus improve the efficiency of this transition, tapered resistive cards were placed between the rim of the antenna and the wall of the test coupler. The receiving end of the device is closed and a dipole is placed approximately $\lambda g/4$ away from the end plate and fed by a single slotted balun, where $\lambda g$ is the guide wavelength for $TE_{11}$ mode. The dipole can be rotated to measure the axial ratio of the transmitted wave and its distance from the end plate is adjustable to maximize power received, after which it can be locked in place. In between the open end of the device and the receiving dipole, three disks made of resistive sheets are placed $\lambda g/4$ apart. The resistance values have been selected to provide approximately 30 dB atten-

uation of the transmitted signal and negligible reflection at either end. Referring to the equivalent circuit for the attenuation section of the coupler, as illustrated in Fig. 10, one finds the following condition for zero reflection:

$$\frac{1}{\frac{1}{1+g_1} + g_2} = g_1 = 1 \qquad (3)$$

or

$$g_2 = \frac{2g_1}{1-g_1{}^2} \qquad (3a)$$

where $g_1$, $g_2$ are conductances of the resistive disks, normalized with respect to the characteristic admittance of the tube (or waveguide), for $TE_{11}$ mode, which is given by

$$Y_c = \frac{1}{\eta}\left[1-\left(\frac{\lambda}{\lambda_c}\right)^2\right]^{1/2} \qquad (4)$$

with $\eta = \sqrt{\frac{\mu_o}{\varepsilon_o}}$ = intrinsic impedance in free space

$\lambda_c = 3.41a$ = cut-off wavelength for $TE_{11}$ mode.

One also finds the transmitted signal is attenuated by

$$\alpha = 20\ \ell og_{10} \frac{1+g_1}{1-g_1} \quad \text{dB} \qquad (5)$$

Using (4) and (5), one can easily obtain the resistance values as indicated in Fig. 9. Note that another resistive sheet, whose resistance is equal to $1/Y_c$, is placed $\lambda g/4$ away from the end plate to improve the termination of the device.

The coupler is calibrated initially when the system is known to be working properly. It was found that the coupling between the output and the input of the device is -30.5 dB, which shows a slight 0.5 dB deviation from the design value. However, the axial ratio detected by the coupler is ~8 dB whereas the antenna is known to have an axial ratio of ~0.5 dB. This is thought to be caused by the fact that, although the dipole lengths are adjusted to radiate circularly polarized waves into free space, they are not necessarily the right lengths for the excitation of circular-polarized wave inside the waveguide provided by the coupler. It can be expected that the situation should improve as the coupler is separated from the cup-dipole. This was proved experimentally and the results are shown in Fig. 11. It is seen that as the separation between the coupler aperture and the base of the cup exceeds $0.8\lambda$, a good indication of the axial ratio of the transmitted signal is obtained. Practically, this separation and the support of the coupler can be provided by the use of a tube made of fiberglass or other materials that have low dielectric constants. This tube may then be wrapped with absorbing material to prevent leakage. It should be detachable since it is not needed for mea-

suring the effective radiated power of the antenna.

## IV. Conclusion

The "cup-dipole" is shown to offer quite significant improvement over its counterpart, the SBF antenna in this application. Based on the development of S-Band models, the following distinct advantages can be summarized for the cup-dipole antenna configuration.

(1) It is an extremely efficient radiator. With a cup size of $1.33\lambda$ in diameter, the antenna can produce a gain as high as 12.7 dB. This is equivalent to an antenna aperture efficiency of 106%.

(2) It has simple and compact construction and can be fed from the transmitter by a standard coaxial cable.

(3) Since the crossed-dipole feed is contained below the aperture, the antenna can be flush-mounted and also protected by a covering.

(4) The axial ratio can be easily adjusted to within 0.5 dB over $\pm 10^\circ$ off boresight over a narrow frequency band.

## Acknowledgment

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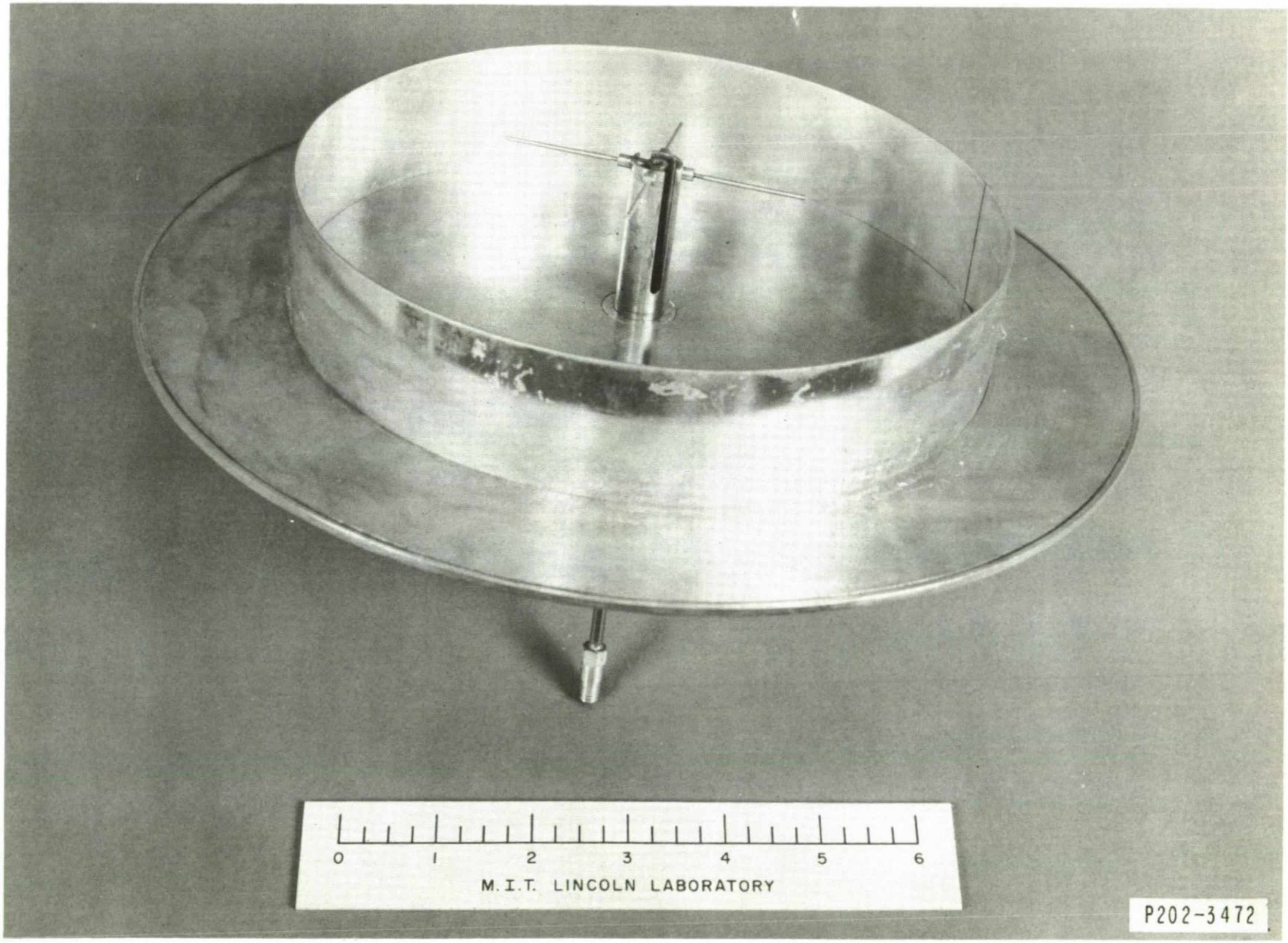


Fig. 1. Prototype test model of S-Band cup-dipole antenna.

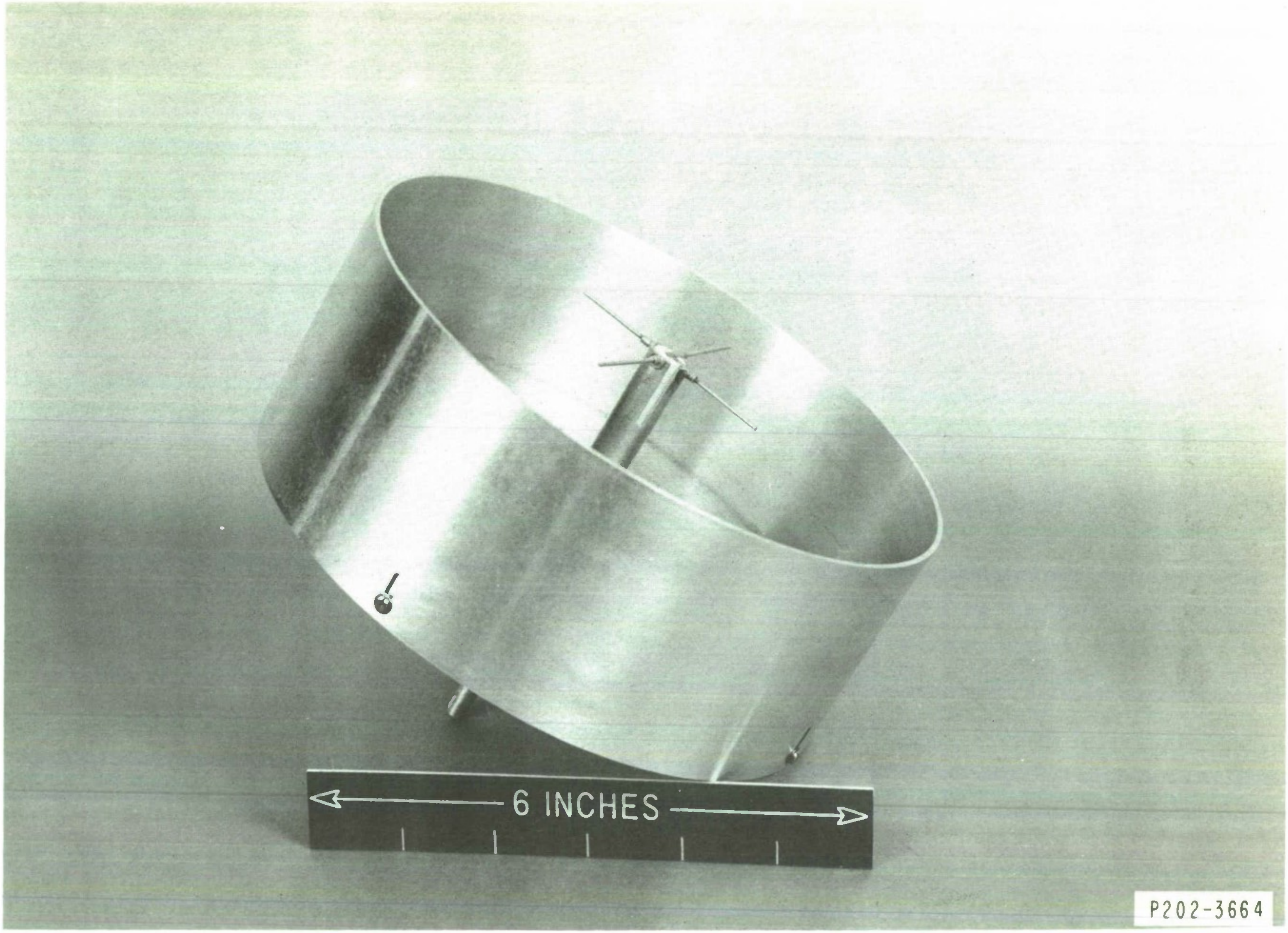


Fig. 2. Second test model of S-Band cup-dipole antenna with coaxial-feed filled with dielectric ($\varepsilon_r \approx 2.0$).

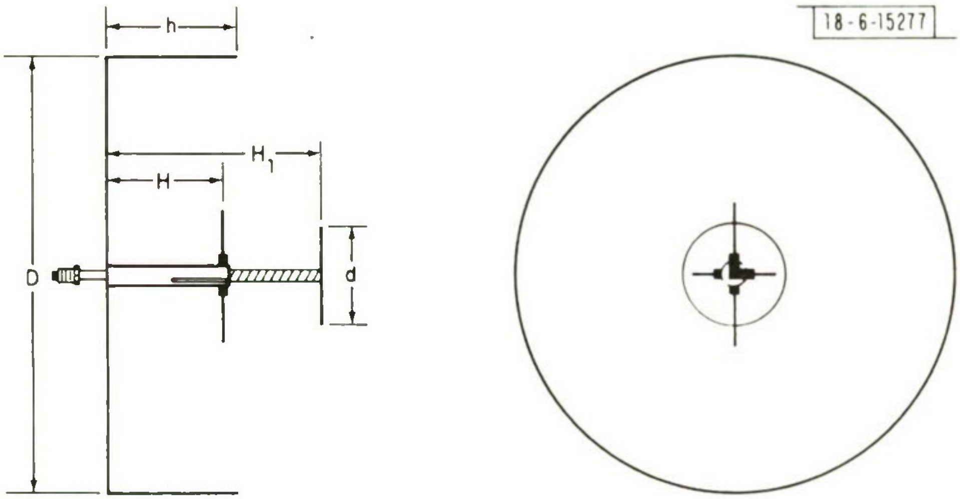


Fig. 3. Geometry of a SBF antenna (d ≠ 0) on a cup-dipole (d - 0) fed by a turnstile feed of crossed dipoles of unequal lengths.

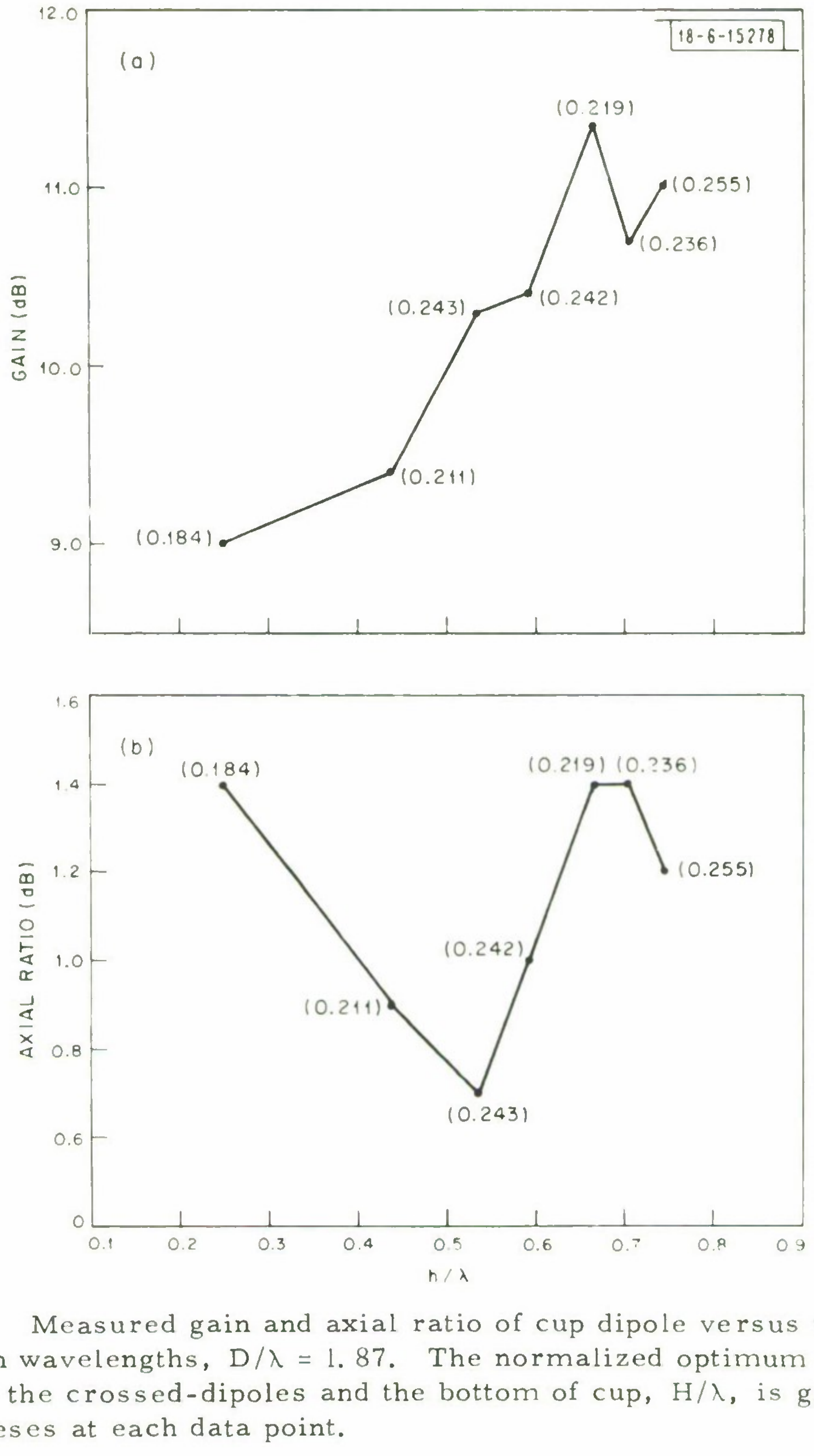


Fig. 4. Measured gain and axial ratio of cup dipole versus the rim height in wavelengths, $D/\lambda$ = 1. 87. The normalized optimum spacing between the crossed-dipoles and the bottom of cup, $H/\lambda$, is given in parentheses at each data point.

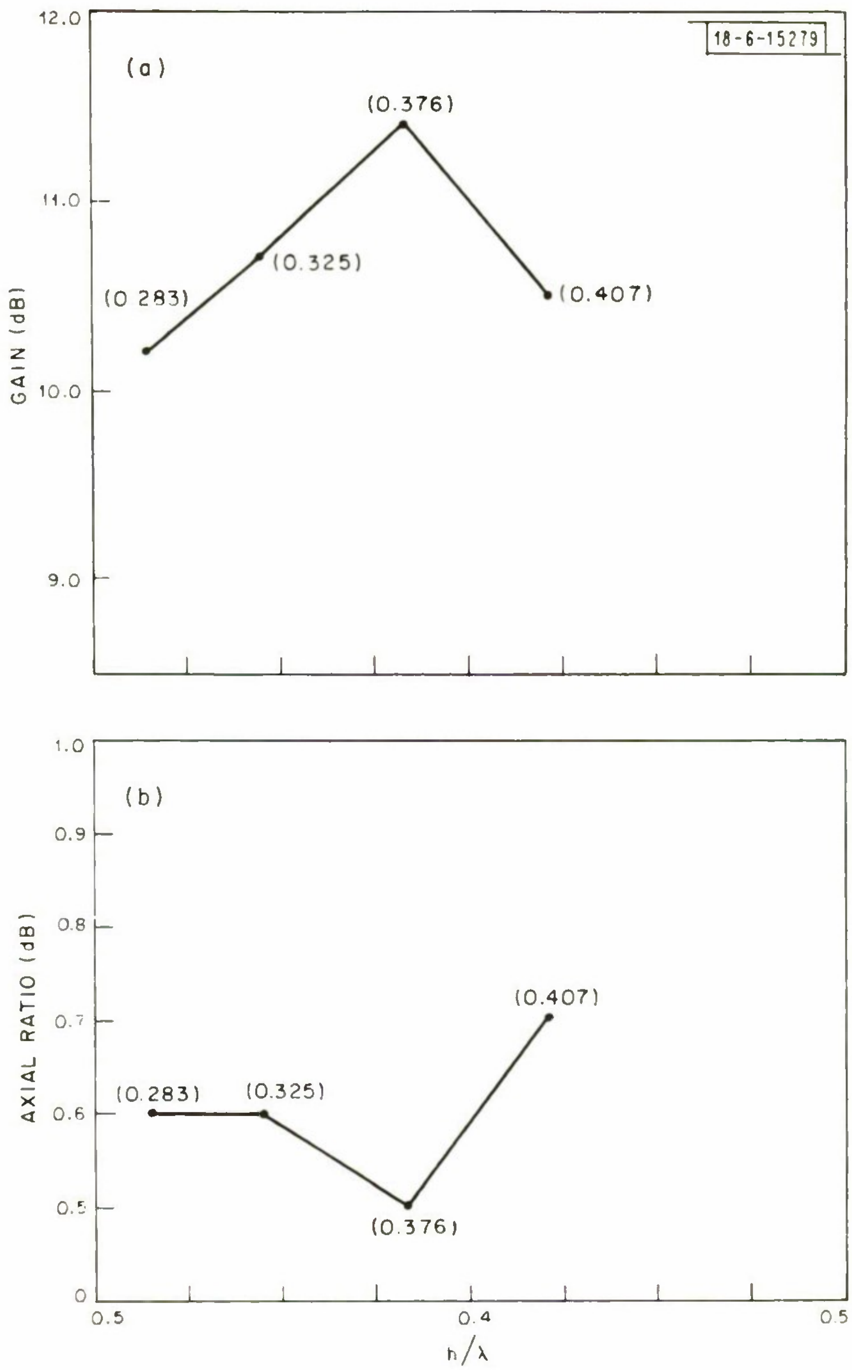


Fig. 5. Measured gain and axial ratio of cup-dipole versus the rim height in wavelengths, $D/\lambda = 1.33$. The normalized optimum spacing between the crossed-dipoles and the bottom of cup, $H/\lambda$, is given in parentheses at each data point.

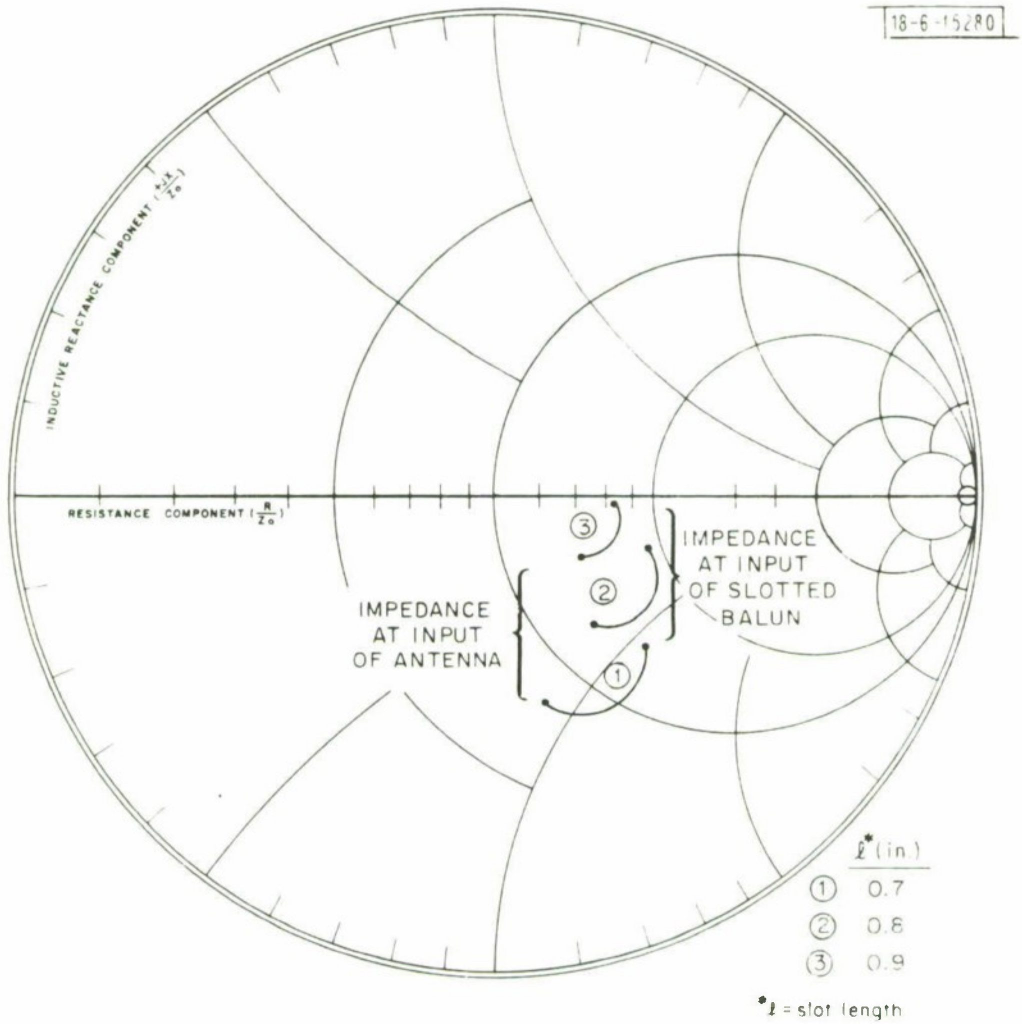


Fig. 6. Impedance characteristics of cup-dipole at 2.245 GHz for different lengths of slotted balun.

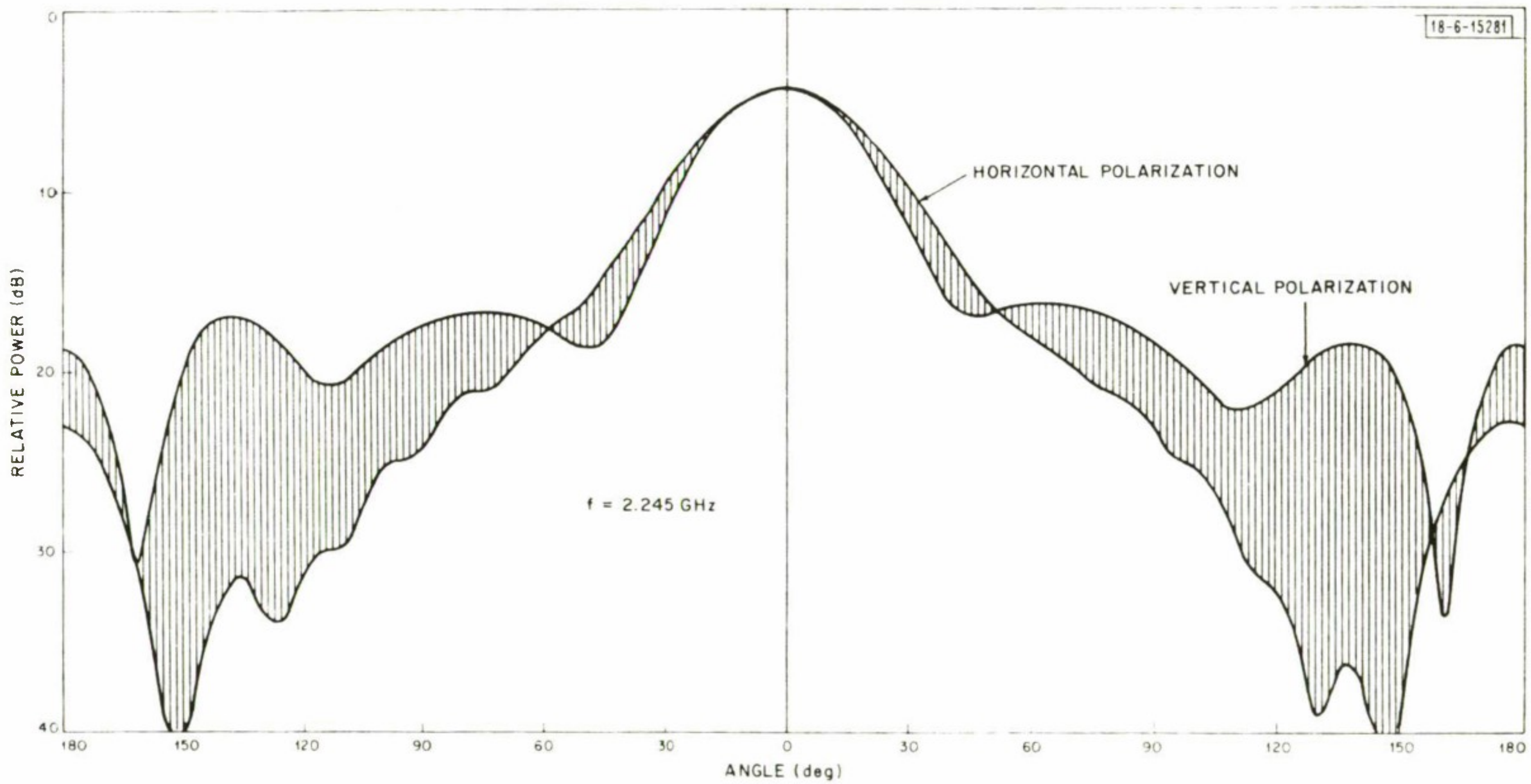


Fig. 7. Radiation patterns of cup-dipole model in Fig. 2.

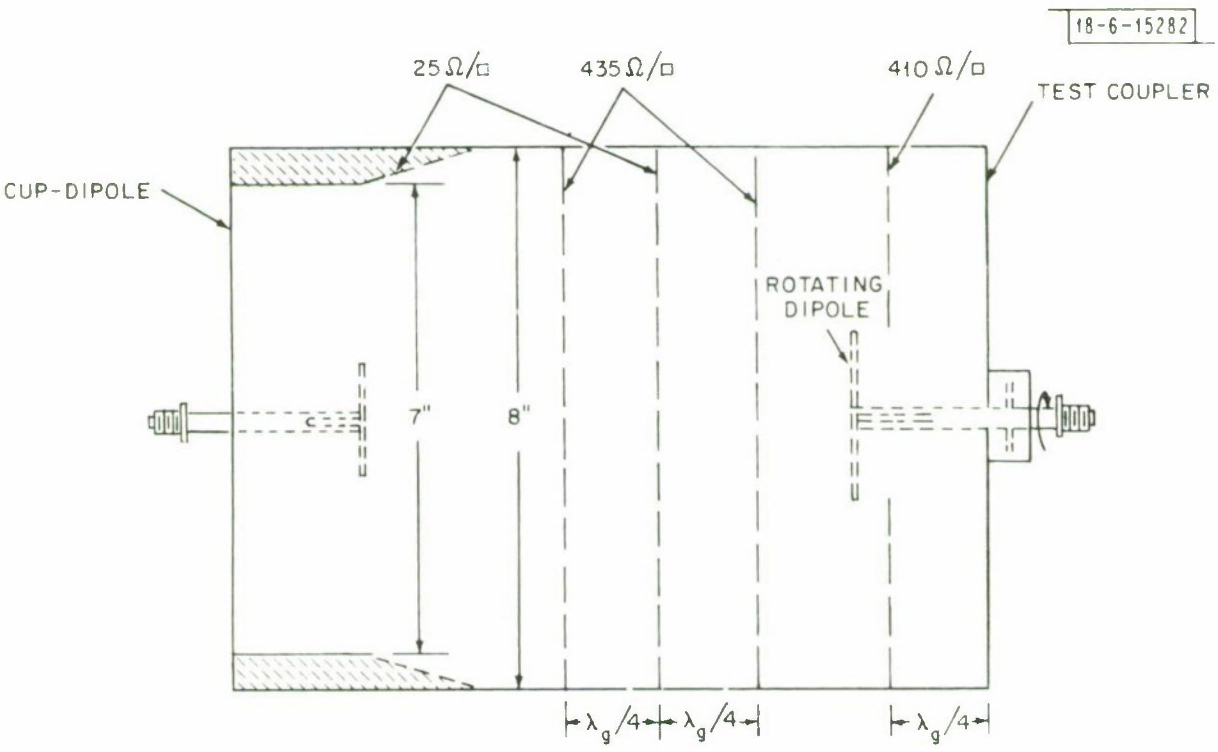


Fig. 8. Construction of test coupler for cup-dipole made in Fig. 2: $\lambda g$ = wavelength of $TE_{11}$ mode at 2.245 GHz.

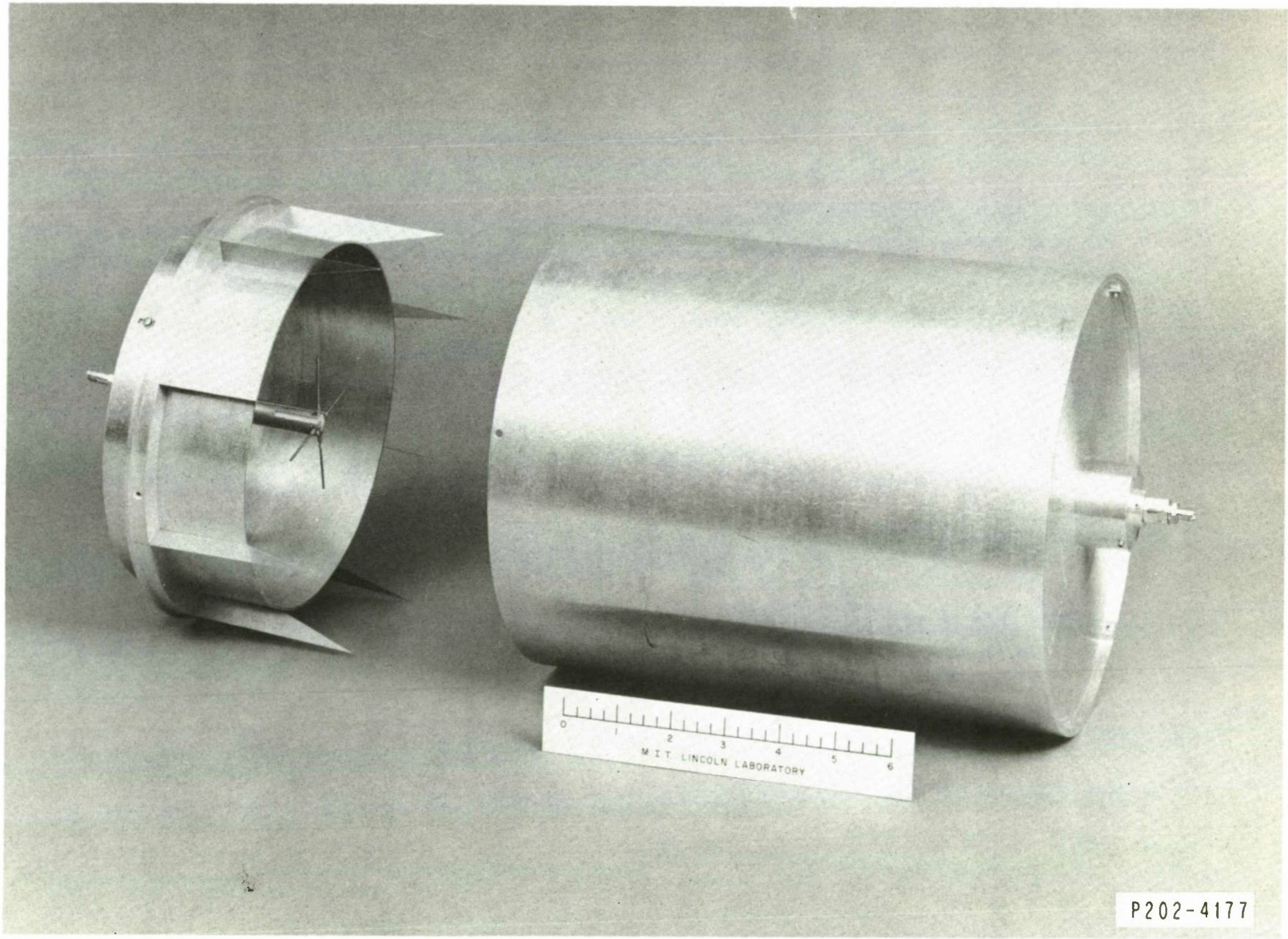


Fig. 9. Test coupler for S-Band cup-dipole in Fig. 2.

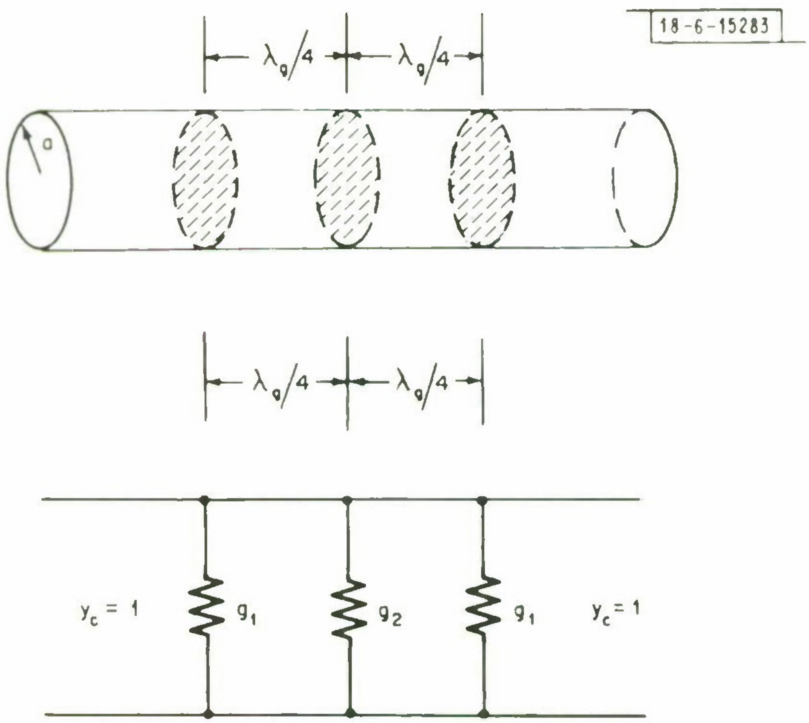


Fig. 10. Symmetrical attenuator made up of three resistive disks and its equivalent circuit.

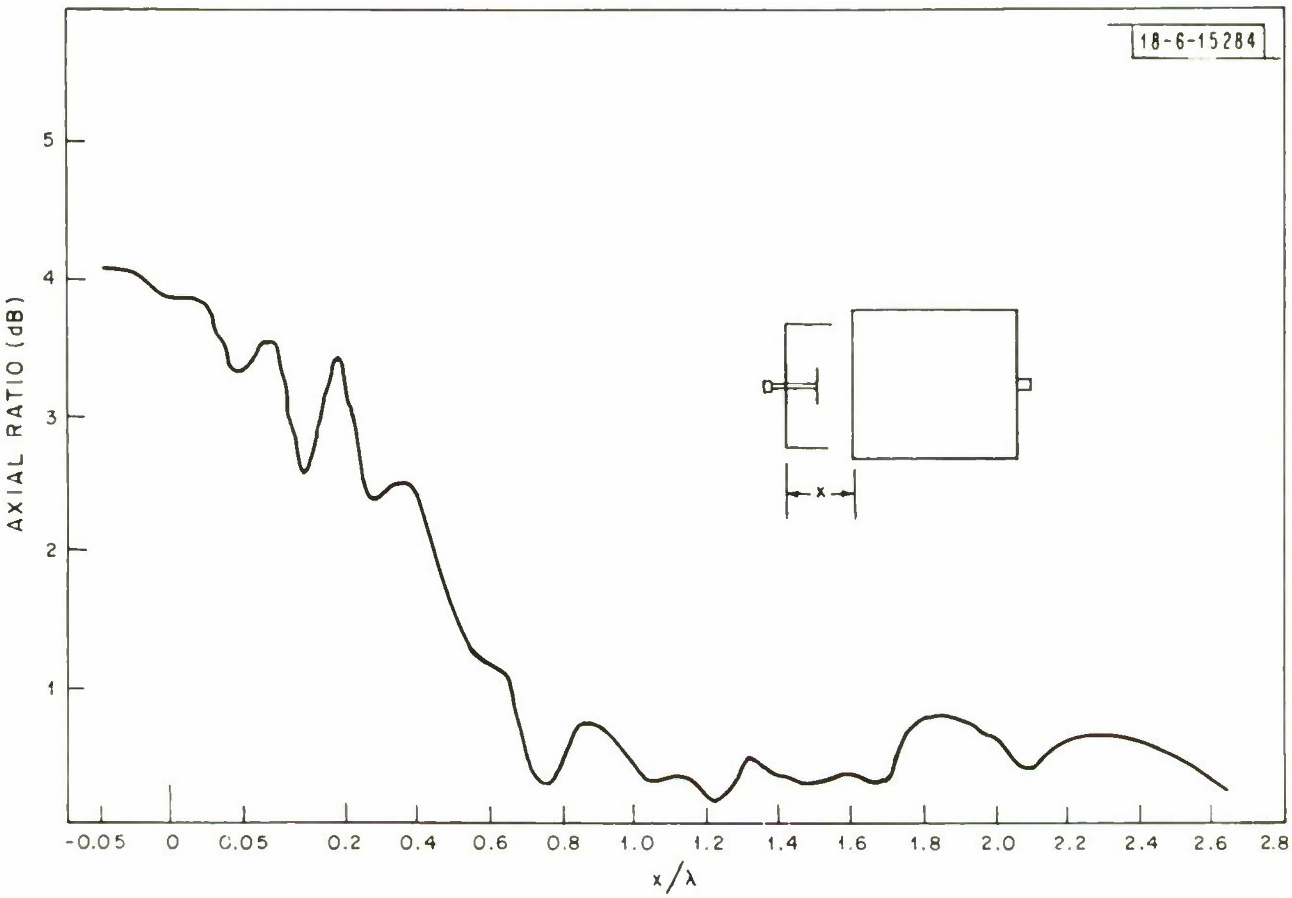


Fig. 11. Axial ratio detected by the test coupler as a function of the distance between the test coupler and the cup-dipole.

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13. ABSTRACT

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The test coupler, which is used to test the performance of the antenna without the necessity for radiating into free space, can attenuate the transmitted signal by 30.5 dB. For a good detection of axial ratio, the coupler needs to be separated at least 0.8λ from the antenna.

14. KEY WORDS

| | |
|---|---|
| S-band antenna | satellite communications |
| test coupler | communication links |
| radiation patterns | |



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